

# Multi-Quark hadrons: Production of $S=-2$ Systems

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The general character of 4-quark (mesonic) and strange 6-quark (baryonic) quark systems is very briefly reviewed a la Jaffe, *i. e.* in the MIT bag, and so far still possibly viable candidates are indicated. The concentration is on the latter ( $S = -2$ ) systems, with some attention given to more likely to be discoverable light, doubly-strange nuclei. The two modes for generating doubly strange, generally double- $\Lambda$  nuclear systems, are considered and related to each other. Traditionally, one employs the  $(K^-, K^+)$  reaction on a relatively light target and hopes to retain two units of strangeness on a single final state fragment. Alternatively, heavy ion reactions can be used to produce  $\Lambda$ -hyperons copiously and one seeks to observe coalescence of two of these particles into the lightest  $S=-2$  nucleus, the H-dibaryon. The complications arising from the presence of a repulsive core in the baryon-baryon interaction on the production of the H are discussed. Also considered is the possible presence in the data from the AGS experiment E906, of slightly heavier  $S = -2$  nuclei, in particular in the system  ${}_{\Lambda\Lambda}^4\text{H}$ .

## I. INTRODUCTION

One very interesting question which arises in our search for macroscopic examples of quark-gluon matter is the apparent absence, or at least the paucity of examples of elementary hadrons possessing more than three quarks. There is perhaps one good candidate for an exotic meson consisting of two quarks combined with two anti-quarks: *viz* the  $\pi_1 1410$  thought to be an  $I^G(J^{PC} = 1^-(1^{-+})$  state [1], but there is not likely an equally good candidate for a  $gg + ggg + \dots$  state or glueball. The perhaps more distinguishable H-dibaryon [2] has also not yet shown up on its own in any experimental search and it has proved to be equally elusive in theoretical analysis. Surely, however, strange matter must be present at the heart of virtually all gravitationally collapsed objects [3]. Nothing new is offered here with respect to the mesonic possibilities: but the presence of more than a single strange quark in dibaryons and light nuclei is explored in more detail.

During this presentation, we wish to cover two apparently disparate subjects: (1) the production of the H-dibaryon in both elementary and heavy ion induced reactions, and (2) the generation of very light to moderately light  $S = -2$  hypernuclei. Both subjects concern  $S = -2$  systems and they are quite possibly tied together by the possible presence within finite systems of a hybrid H, possibly constructed both from dibaryon  $\Lambda\Lambda$  and from 6-quark bag like ( $uuddss$ ) components, *viz*:

$$|\Psi\rangle = \alpha|\Lambda\Lambda\rangle + \beta|q^6\rangle \quad (1)$$

with  $\alpha, \beta$  being amplitudes for the two-body and 6-quark components of the hybrid state. The purely Jaffe-like H state [2] corresponds to  $\beta = 1$ . Our coalescence calculation is independent of this parameter. The procedure we follow to estimate the effect of the hard core on entry from a doorway  $\Lambda\Lambda$  state into the final H is applicable to either the pure bag or hybrid cases.

We begin by indicating that the seeming absence of the H in existing searches is perhaps attributable to repulsive (soft-core) forces in the baryon-baryon system, which prevent penetration to short range of a  $\Lambda\Lambda$  pair during any mechanism for formation of the dihyperon structure. However, one might anticipate to the contrary, that within a finite nucleus two  $\Lambda$ s could be held together for sufficient time to permit a short range structure to develop.

Since the first of these subjects, H-suppression, has been described elsewhere [4], it will only be briefly dealt with here. To our knowledge all theoretical estimates of production rates [5,6], irrespective of mechanism, have overlooked the possibility of a repulsive core in the baryon-baryon interaction at short distances. As we show, under reasonable assumptions the core can lead to an appreciable diminution of H yield. We introduce this device in the context of heavy ion collisions where a previous calculation [6] suggested a high formation probability,  $\sim 0.07$  per central Au + Au collision. The AGS experiment E896 [7] is presently analysing some 100 million central Au + Au events and could, in the light of this previous estimate, have provided a definitive search for the H. In Reference [4] we presented an estimate of the extent to which a repulsive core might interfere with this hope.

We put forward first the simplest possible theoretical description of the multi-quark systems; then we consider the, successful or otherwise, experimental searches for such objects. This is followed by a description of the related attempts to produce multi-strange nuclei.

## II. BAG MODEL ANALYSIS OF MULTI-QUARK STATES

Soon after the introduction of the MIT bag [8] model, used to consider the normal hadrons, mesons constructed from a single quark-antiquark pair and baryons containing three quarks, Jaffe [2] proposed the insertion into the bag of extra valence quarks could produce more exotic systems. For meson states these additional components could be quarks only  $(q\bar{q})^2$  or could be hybrids of quarks and glue  $(q\bar{q}, g)$ . Glueball states,  $(gg + ggg + \dots)$ , were already on the table. Jaffe also suggested the existence of the H-Dibaryon which could be described as a 6-quark bag (uu,dd,ss) [2]. Of course, the easiest meson candidates to identify would be the so-called exotics, *i. e.* those with quantum numbers which cannot arise from  $(q\bar{q})$  alone. Examples of exotic quantum numbers are states characterised by  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ .

The basic theory covering all these states in the bag model is essentially the same. The total energy for N quarks in a bag of radius R may be written [2]:

$$E(N) = E_Q + E_V + E_0 + E_G \quad (2)$$

with a quark kinetic energy

$$E_Q = \frac{1}{R} \sum_{i=1}^N [k(m_i R)^2 + (m_i R)^2], \quad (3)$$

where  $k$  is a wave number, and

$$E_G = -\frac{g^2}{2} \sum_{i<j} \sum_{a=1}^8 \int d^3x (\bar{B}_i^a \cdot \bar{B}_j^a) = -\frac{\alpha_c}{R} \sum_{i<j} \sum_{a=1}^8 M(m_i R, m_j R) [\bar{\sigma}_i \cdot \bar{\sigma}_j] (\lambda_i^a \lambda_j^a). \quad (4)$$

Here  $M(m_i R, m_j R)$ , is the color magnetic energy of one-gluon exchange from quark to quark. The other terms  $E_V = BV$  and  $E_0 = -z_0/R$  are the volume bag pressure and the bag zero point energy respectively. The bag parameters suggested by analysis of the normal hadron spectrum involve a rather large gluon exchange coupling  $\alpha_c = (g^2/4\pi) = 0.55$ , a bag constant  $B^{1/4} = 146$  MeV, vacuum energy  $z_0/R = 1.84$ , and finally a rather large mass for the strange quark,  $m_s = 279$  MeV. The matrix element,  $M(m_i R, m_j R)$ , obtained in the bag for the color-magnetic operators is approximated by a diagonal matrix for strange quarks;  $M = M((n_s/N)m_s R, (n_s/N)m_s R)$  with  $n_s$  the number of strange quarks.

To proceed, one constructs anti-symmetric wave functions in color, spin and flavour, diagonalises the energy exploiting the existing  $SU(6) = SU_c(3)XSU_S(2)$  symmetry and then minimises the whole with respect to bag radius. The general range found for the masses of  $(q\bar{q})^2$  states is from 1460 MeV ( $S = 0$ ) to 2140 ( $S = 4$ ) MeV. A reasonably good candidate for such an exotic is the  $\pi_1(1400)$ , referred to above [1], identified in  $\pi^-N$  scattering. In particular Thompson *et al.* [1] find a resonant final state  $(\eta, \pi^-)$  component to which they assign a mass of  $1370 \pm 10_{-30}^{+50}$  MeV and a width of  $385 \pm 40_{-105}^{+65}$  MeV. No state of similar status has been isolated for other quark hybrids or glueballs.

The  $S = -2$  H-dibaryon, considered more extensively hereafter, is found by Jaffe, through reasoning similar to that above, to be some 80 MeV bound.

## III. H-DIBARYON

This highly symmetric object is in principle more likely to exist than its meson-like compatriots. The H possesses conserved baryon and strangeness numbers, *viz*  $B = 2, S = -2$ . If it were a purely hadronic state its wave function would appear as

$$\Psi_H = \sqrt{\frac{1}{8}}|\Psi_{\Lambda\Lambda}\rangle + \sqrt{\frac{3}{8}}|\Psi_{\Sigma\Lambda}\rangle + \sqrt{\frac{4}{8}}|\Psi_{\Xi N}\rangle. \quad (5)$$

More recent estimates of the mass of the H have differed from Jaffe's original estimate and from each other. Indeed, there is no consensus among theorists that the H is in fact a bound object. There is, however, general agreement on the results of the many searches which have been made for this state: it is not yet found.

Conventional hypernuclear studies [5] exploit the elementary processes  $p(K^-, K^+)\Xi^-, p(\Xi^-, \Lambda)\Lambda$ . The first produces an effective  $\Xi^-$  beam, incident on another nucleus in the target and generating a di-lambda. The latter pair may or may not form the putative H. The same experimental approach could of course yield doubly strange hypernuclei. An

advantageous target for the  $\Xi^-$  beam is the deuteron, resulting hopefully in an H plus a monoenergetic neutron. The latter is relatively easily identified.

Another approach, used in the BNL experiment E896 [7] exploits the large numbers of  $\Lambda$ s, some 30 per event, generated in relativistic  $Au + Au$  collisions. Here again the results have been so far negative.

One good reason for the lack of success of these experiments lies in the nature of the production of a bound di- $\Lambda$  state. For two strange baryons to coalesce into a bag they must first penetrate the mutually repulsive core of the potential. Suppression of the yield for a spatially very extended object like the deuteron is minimal. This is not so for the H, which consists of six quarks in a bag comparable in size to that of a single baryon, so that short range repulsion, found in  $NN$  interactions and expected to exist for strange baryon-baryon interactions as well, could play a considerable role. H formation from two  $\Lambda$ s can be viewed as proceeding in two steps: merging into a broad deuteron-like state followed by barrier penetration into the bag. The overall rate is then proportional to the product of the probability of coalescence [9] with a prefactor giving the penetration probability. Of course there are unknowns, one the  $\Lambda\Lambda$  separation  $a$  at which the two bags would dissolve into a single bag, the other the nature of the short range forces after dissolution. The first,  $a$ , we treated as a parameter; the second we took from the Bonn potential [10], limiting our considerations to the shortest ranged  $\omega$  and  $\sigma$  components. Since the exchange of a  $\phi$  meson between  $s$  quarks very nearly matches that of an  $\omega$  between ordinary quarks, the Bonn interaction needs little readjustment for strange-strange interaction. Thus we take the short range force, appropriate to the penetration of the core and depicted in Fig. 1, to be of the form

$$V(r) = V_\omega(r) + V_\sigma(r), \quad (6)$$

where

$$V_i(r) = \frac{g_i}{r} \exp(-m_i r). \quad (7)$$

The strong short range  $\sigma$  attraction reduces the effect of the hard core, while the longer range parts of the force are assumed to play a negligible role. The two baryons approach to some outer radius  $b$ , in fact a turning point, before being faced with the strong repulsion. The calculation is especially sensitive to this ‘separation’  $a$ . Although, our final results on barrier penetration are consequently somewhat uncertain, it will become apparent that the one thing one cannot do is to ignore them.

Barrier penetration in this effective two body model can be quantified in the transmission coefficient [11] at relative energy  $E$ ,

$$T(E) = 4 \exp(-2\tau), \quad (8)$$

where

$$\tau = \int_a^b dr \sqrt{2m(V(r) - E)}. \quad (9)$$

The chief results, as they relate to the coalescence into di-baryons in  $Au + Au$  collisions, are presented in Fig. 2, indicating the variation of H-dibaryon yield with  $a$ . This latter parameter must not be thought of as an effective hard core radius for the  $\Lambda - \Lambda$  interaction. The underlying quark-quark forces may be viewed as possessing a repulsive short range component due to the exchange of vector mesons [12]. Even with complete overlap of the parent baryons the average interquark separation for a uniform spatial distribution is comparable to the parent radius  $R \sim 0.8$  fermis, i. e. considerably greater than any conceivable fixed hard core. We have concentrated on baryon centers between 0.25 and 0.40 fermis apart as reasonable.

At the largest of separations suppression from the repulsive forces is not inconsiderable, but for the smallest  $a$ -values observation of the H, should it exist, becomes a serious problem. Early analysis of the actual experimental setup using the heavy ion simulation ARC [13,14], suggested a neutral background comparable with the initial estimate of 0.07 H’s per central collision. For baryon separations of 0.25 to 0.35 fermis one would have to achieve a tracking sensitivity of  $10^{-4}$  to  $10^{-2}$  relative to background. In the worst case scenario one is still left with perhaps a few thousand sample dibaryons, from the very large number of central  $Au + Au$  events; but immersed in what may prove to be a daunting background.

We conclude short range repulsion between strange baryons can profoundly hinder coalescence into objects whose very existence depends on the presence of important bag-like structure. This lesson applies even more so to the many H-searches initiated by  $(K^-, K^+)$  reactions [5], since these generally involve even lower relative energies  $E$ . Unfortunately the very same repulsive forces which made coalescence into a bound state difficult, may, at the quark level, destroy the existence of any such state.

#### IV. DOUBLY STRANGE HYPERNUCLEI

There is perhaps one way to circumvent this frustrating barrier to the discovery of the lightest of all possible strangelets. In the event a pair of  $\Lambda$ 's is attached, through a  $(K^-, K^+)$  reaction, to a light nucleus, a hybrid  $H$  may form, i. e. the  $H$  described above containing both di-baryon and six quark bag components. In a light nucleus, for example  ${}_{\Lambda\Lambda}^4\text{H}$ , the extra nucleons in this four particle system keep the captured hyperons together for some 100 picoseconds, far more than enough time for penetration of the rather modest 1 – 2 GeV barrier between them. In any case the search for  $S=-2$  hypernuclei, the only strangelets we are certain exist, is highly interesting in its own right. An ongoing AGS experiment, E906 [15], focuses on these nuclei and as we indicate may have already provided evidence for their existence [15].

In E906 [15]  $(K^-, K^+)$  reaction on a  ${}^9\text{Be}$  target is employed to produce a tagged beam of  $\Xi^-$ 's. The  $\Xi^-$  in turn may convert into a pair of  $\Lambda$ 's by interaction with a proton, either in the nucleus in which it was produced or by subsequent interaction with another  ${}^9\text{Be}$  nucleus. It is in an emulsion experiment at KEK [16] that one such hypernuclei was found with perhaps other examples from Prowse [17] and Danysz et al [18]. Indeed, all three of these candidates for double hypernuclei were interpreted as possessing a  $\Lambda - \Lambda$  pairing energy  $\Delta B_{\Lambda\Lambda} \sim 4.5$  MeV [19]. Such a high value is unexpected from existing, albeit theoretical, knowledge of hyperon-hyperon forces. It was then possible to surmise interesting activity in the  $\Lambda - \Lambda$  system at short range separation.

Given the  $K^-$  beam energy of 1.8 GeV, initially the tagged  $\Xi^-$ 's possess considerable kinetic energy,  $\sim 140$  MeV, and are more likely than not to escape the nucleus in which they are produced. A guiding principle we employ in qualitatively understanding the broad aspects of the data, is that final states containing the very stable  ${}^4\text{He}$  are favoured. This picture is also mindful of an oft used cluster model for  ${}^9\text{Be}$  as two  $\alpha$ 's joined together by a weakly bound neutron. The  ${}^9\text{Be}$  target is useful in slowing down the  $\Xi^-$ , but the observed reactions are for the most part initiated essentially on an  $\alpha$ .

Further, in the present experiment which observes  $S=-2$  final states by their decay into two momentum-correlated  $\pi^-$ 's, the heaviest  $A=9,8,7..$  systems will weak decay predominantly through non-mesonic channels. Thus the lightest systems are probably doubly favoured in our data, through both their production and decay dynamics.

#### V. ANALYSIS OF THE E906 DATA

The measurements which contain evidence for possible  $\Lambda\Lambda$  hypernuclei are highlighted in Fig. 3. Displayed are the two-dimensional, Dalitz plot for the total sample of correlated two  $\pi^-$  decays recorded in the CDS detector [15], and the projections of this data on the  $P_L$  and  $P_H$  axes. These denote the low and high momenta for the  $\pi_L$  and  $\pi_H$  pair detected in an event. The circled feature in the 2-D plot is of principle interest, giving rise to the prominent peaks near  $P_H = 114$  MeV/c in insert I and a correlated peak at  $P_H \sim 104$  MeV/c in II. The experiment is searching for pairs of pion momenta unexplained from previous knowledge of hypernucleon lines. The expected spectrum close to the region of interest in E906 are shown in Fig. 4, with single hypernuclear lines indicated vertically and doubly strange candidates diagonally. The slope in the latter denotes the dependence of the  $S = -2$  energy as a function of the important pairing energy  $\Delta B_{\Lambda\Lambda}$ .

The higher momentum structure in I near 137 mev/c is understood as the decay in flight of  $\Xi^-$  hyperons, but the width of the lower peak is too broad to be due to a single component line. The very prominent peak in II is completely unexpected. The high momentum  $\pi^-$  peak in I arises in part from the decay of  ${}_{\Lambda}^3\text{H}$  yielding a meson line at 114.3 MeV/c, but considering the experimental resolution of 2.5 MeV, this  $\pi_H$  prominence at 114 meV must contain more structure.

The projection in II is constructed from a reverse cut  $106\text{MeV}/c \leq k\pi^- \leq 120\text{MeV}/c$ , i. e. under the first compound peak in II, and thus should reveal the low momentum  $\pi_L^-$  correlated with the 114 MeV/c peak in I. The most striking feature in II is the narrow prominence near 104 GeV/c, which cannot for example be accounted for by single  $\Lambda$  decay in a  ${}_{\Lambda}^3\text{H} + \Lambda$  final state, or for that matter by any other known line. Adding even a small kinetic energy to the  $\Xi^-$  initiating the reaction leading to the final  $S=-2$  state would broaden the single  $\Lambda$  decay well beyond that measured for the the dominant peak in this reverse cut. The correlation of this peaking II with the excessively broad dominant peak in Fig. 3 I is strong evidence for the presence of a light double- $\Lambda$  species in the data.

Fig. 4, [20], indicates where known single  $\Lambda$  hypernuclear lines are expected as well as where  $S = -2$  lines are anticipated as a function of the pairing energy  $\Delta B_{\Lambda\Lambda}$ . Reiterating, the most interesting feature in the present data, centered at 112 – 114 MeV/c, could only result from the production of  ${}_{\Lambda\Lambda}^4\text{H}$  and/or  ${}_{\Lambda}^3\text{H}$ .

${}_{\Lambda\Lambda}^4\text{H}$  has two generic modes of decay:

$${}_{\Lambda\Lambda}^4\text{H} \rightarrow {}_{\Lambda}^4\text{He} + \pi_2^-, \quad (10)$$

or

$${}_{\Lambda\Lambda}^4\text{H} \rightarrow {}_{\Lambda}^3\text{H} + p + \pi_1^- . \quad (11)$$

The two body decay in the first mode yields the high energy  $\pi_2^-$  from which the  ${}_{\Lambda\Lambda}^4\text{H}$   $\Delta B_{\Lambda\Lambda}$  can in principle be estimated, and is followed by a three body decay producing the correlated  $\pi_1$ .

The very narrowness of the  $\pi_1^-$  peak in II suggests the decay mode in Equation 7 is not strictly three body in character. We offer as a candidate a resonance in  ${}_{\Lambda}^4\text{He}$ , arrived at by decay from the clearly spatially extended  ${}_{\Lambda\Lambda}^4\text{H}$  and thus not favoured in production from  $K^- + {}_{\Lambda}^4\text{H}$ . The first, lower,  $\pi_1^-$  momentum from the initial decay would then be sensitive to the sum  $E_R + \Delta B_{\Lambda\Lambda}$ . Preliminary theoretical calculations [21] indicate that indeed a narrow P-wave resonance can be placed near  $E_R = 0.5 - 1.5$  MeV in the  $p + {}_{\Lambda}^3\text{H}$  system, using a potential consistent with the rather extended geometry of  ${}_{\Lambda}^3\text{H}$  and constrained by the known proton binding in the ground state of  ${}_{\Lambda}^4\text{He}$ .

## VI. COMMENTS AND CONCLUSIONS

There is little to add to the above discussion of multi-quark elementary systems. The search for an  $H$  is certainly complicated by our analysis of its formation. The discovery and study of  $S = -2$  hypernuclei will, however, continue, either at the AGS or the expected Japanese Hadron Facility.

For E906 there were 1040 events in the total two prong sample, some 70 above background in the first feature in Fig. 3 I. The reverse cut in II can be used to isolate the three body decays of  ${}_{\Lambda\Lambda}^4\text{H}$  and from the simulation an estimate of the two body, resonant, decays can also be made. We conclude then a lower limit of  $40 + 20$   ${}_{\Lambda\Lambda}^4\text{H}$  have been produced in these two modes respectively. Unfortunately, the important di- $\Lambda$  pairing energy is not well determined in the present experiment. A simulation of Fig. 3 I suggests  $\Delta B_{\Lambda\Lambda} \sim 1 - 2$  MeV while that in Fig. 3 II involving the combination with  $E_R$  is perhaps described by a value closer to  $0.5 - 1.0$  MEV. More recent emulsion experiments [22] have definitively identified the species  ${}_{\Lambda\Lambda}^6\text{He}$  and agree with the lower values of  $\Delta B_{\Lambda\Lambda}$ , finding something less than 1 MeV. The motivation for a hybrid  $H$  living within some light nucleus then recedes.

Clearly, better statistics and an improvement in resolution are required to determine  $\Lambda\Lambda$  pairing energy definitively, and more importantly to establish the actual presence of the large numbers of light doubly strange hypernuclei suggested by E906. The principal issues to be settled, presumably in a follow on experiment, are the existence or not of more than one contribution to the broad lower peak in the higher momentum  $\pi_2^-$  spectrum and the very exciting possibility that more than one species of double  $\Lambda$  resides in the data. Significantly higher counting rate should allow cuts to be placed on the  $\Xi^-$  kinetic energy and determine the nature of the reaction mechanism producing individual doubly strange species.

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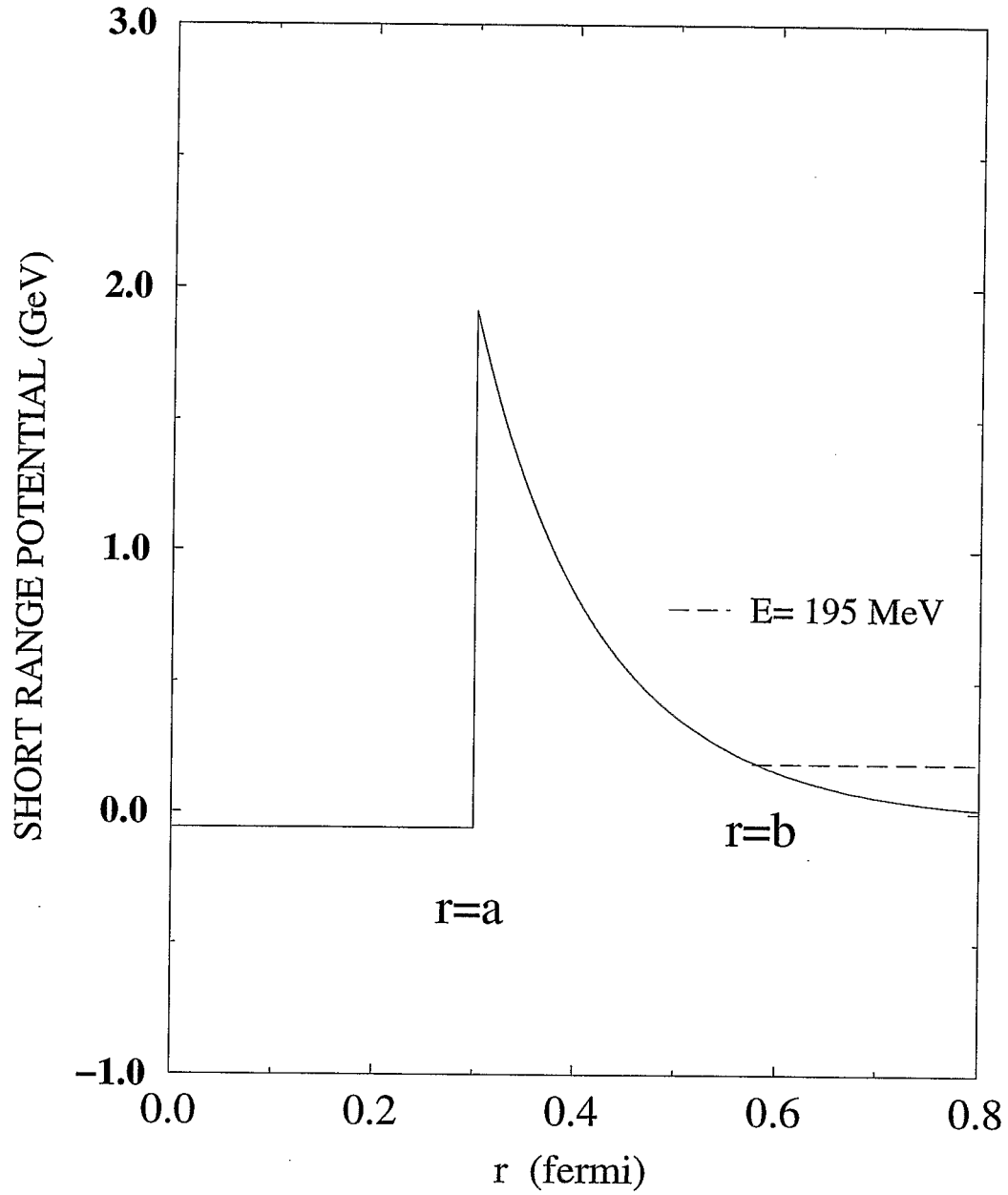


FIG. 1. The short range  $\Lambda$ - $\Lambda$  potential taken from the  $\sigma$  and  $\omega$  exchange parts of the Bonn potential. At some separation  $a$  the two strange baryons are assumed to dissolve into a single bag, represented here by a shallow, attractive potential. Barrier penetration at relative energy  $E$  from the di- $\Lambda$  doorway state is represented by the dashed line.

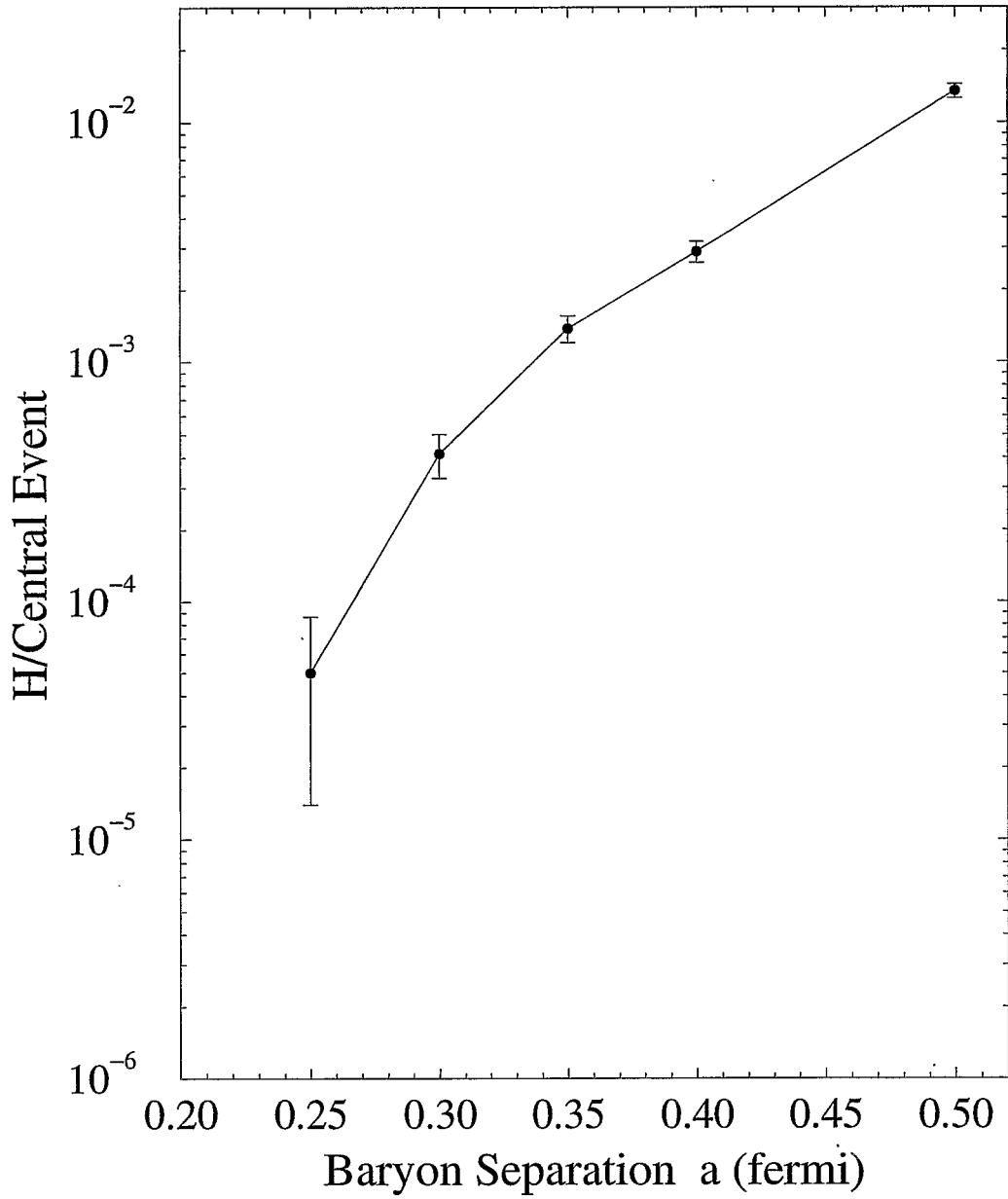


FIG. 2. Absolute H Production per Central  $Au + Au$  at 10.6 GeV . The precise separation of di- $\Lambda$  centers,  $a$ , at which a single six quark bag forms is of course not known, but a reasonable value is likely less than 0.3 fm. Even for complete baryon overlap, the average distance between constituent quarks is greater than the conventional nucleon-nucleon hard core radius of 0.4 fm.



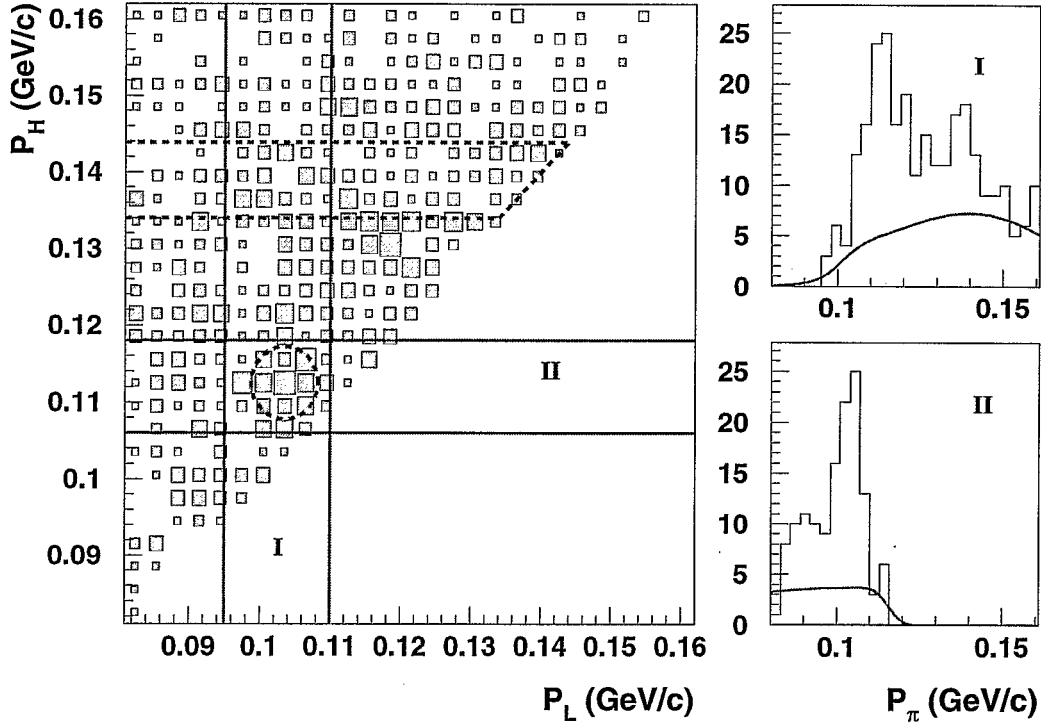


FIG. 3. The E906 two Pion Data. The Dalitz plot together with projections onto high (inset I) and low (inset II) momentum axes describe the approximately 1000 recorded, correlated,  $\pi^-$  events. The interesting region is circled in the 2-D plot. I contains a broad  $\pi_H$  peak with components from  $\Lambda^3\text{H}$  and the two-body decay of  $\Lambda\Lambda^4\text{H}$ . Inset II contains an unexpected narrow  $\pi_L$  peak interpreted as arising from an alternative decay of  $\Lambda\Lambda^4\text{H}$  involving a resonance in  $\Lambda^3\text{He}$ .

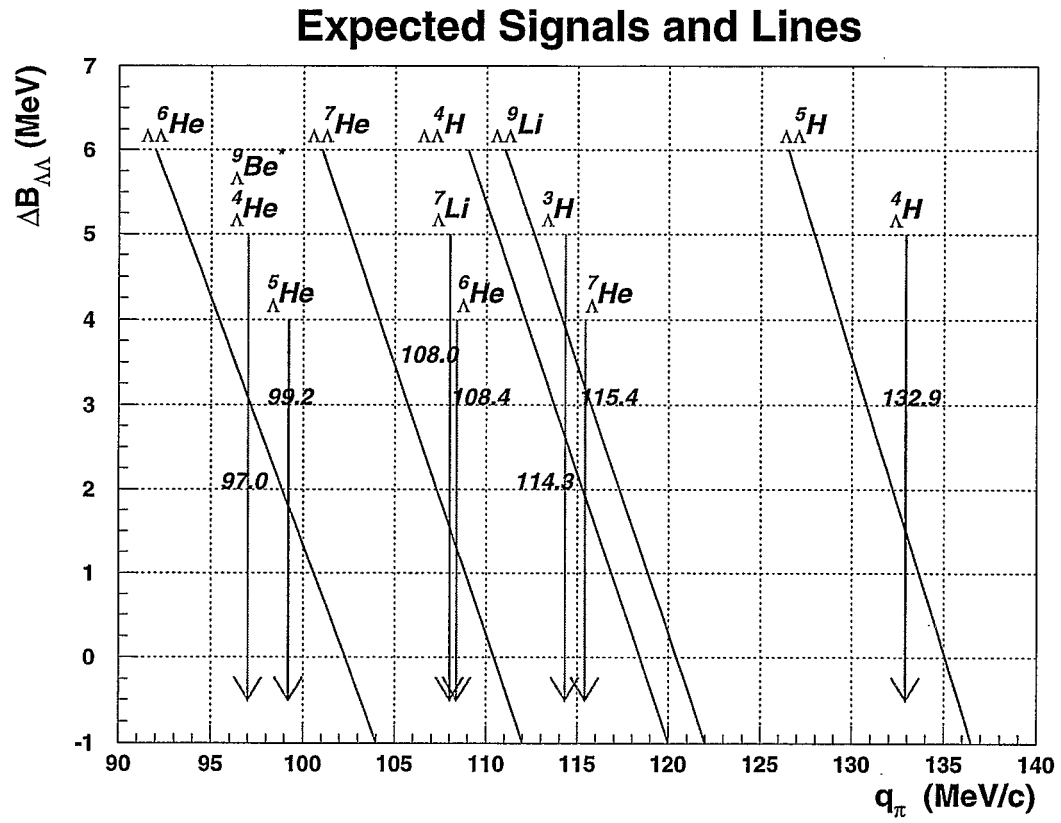


FIG. 4. Expected  $S = -1$  lines together with possible doubly strange hypernuclear energies, the latter as a function of the pairing energy  $\Delta B_{\Lambda\Lambda}$ .